A GaAs MESFET IC for Optical Multiprocessor Networks

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Abstract—A GaAs, E/D mode, self-aligned, refractory-gate, MESFET chip process and circuit family has been developed for the integration of fiber-optic data link functions (e.g., photodetection, amplification, clock recovery, and deserialization) on a single chip. This paper describes the process and presents results on integrating a complete optical receiver, including the photodiode and clock recovery circuits, onto one chip. The chip functions use over 2000 devices, and perform at 1-Gbit/s speed, while dissipating less than 300 mW of heat. This chip is the most complex high-performance OEIC reported to date.

I. INTRODUCTION

THE interconnection of many processors is a growing theme in the data processing industry [1], [2]. For optical data links to play a role in the interconnection networks of these multiprocessor complexes, a high-performance reliable, compact opto-electronic integrated circuit (OEIC) technology is needed to integrate network functions together on a single semiconductor chip [3]. Typical functions implemented at network interfaces, which would be important to capture on a chip are shown in Fig. 1, and include a mix of digital and analog, and optical and electronic functions, with a chip complexity at the LSI level. With powerful processors at the network nodes, multi-gigabit-per-second speed may be required in this chip (for example, [4]¹). The distances are likely to be short (less than 1 km) to keep data transit times between the nodes short with respect to the machine instruction cycle time.

This paper describes a GaAs MESFET IC process that has many of the characteristics desired for this application. At this time, it appears that GaAs is the best technology candidate, as other implementations (e.g., based on Si or InP material systems) will be limited to bulky hybrid chip modules, low levels of integration, and yield

and reliability concerns due to transistor limitations or complex strained layer epitaxial growth techniques [5], [6].

We also present experimental results on the integration of some key functions onto a single chip, performing at gigabit-per-second data transfer rates. The chip described represents the highest level of integration yet reported in integrated gigabit-per-second opto-electronics chips.

II. MESFET OEIC

Refractory-gate MESFET processes have gained favor for GaAs logic and memory applications because they are simple, provide good thermal stability of device characteristics, and offer potential for the reduction of device parasitic resistance and capacitance [7]. The self-aligned gate MESFET technology employed in fabricating the chip reported here is an enhancement of that described previously by some of the authors [8], with significant changes in lithography and wiring, and the incorporation of gate sidewalls with a moderate implant beneath them. The process employs $^{47}\text{SiF}^+$ channel and source-drain implants, sputtered $\text{WSi}_{0.11}$ refractory gates, Ni-Au-Ge ohmic contacts, Si_3N_4 and SiO_2 insulation, and Ni-Au wiring. A gate length of 1 μm was used in all circuits. The FET channel and photodetector implant was activated by furnace annealing either in an arsenic overpressure or with a SiN_xO_y cap deposited by plasma-enhanced chemical vapor deposition (PECVD). Furnace annealing of the source-drain implants was carried out with a Si_3N_4 cap. Following patterning of the gate and detector electrodes, a moderate-dose self-aligned implant was carried out, after which a blanket Si_3N_4 layer was deposited and etched to leave triangular sidewalls at the edge of the gate. The sidewalls keep the heavy source-drain implant away from the gate edge, resulting in a reduction in gate capacitance and an improvement in breakdown voltage.

The lithography for these circuits, which have 11 masking levels, was carried out entirely by step-and-repeat projection lithography. Positive photoresists were used except for the gate and wiring levels. For these levels, a negative-tone image-reversed structure was used for optimum resolution (for the gate etch), and for retrograde

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¹For example, the recently announced CRAY Y-MP/832 transfers data from RAM storage into an eight-processor "host" over channels at up to 1 Gbyte/s.

Fig. 1. Network interface functions: The typical functions required for an interface to a network. For full duplex operation, both sets of functions would be required at each network node. The shaded functions are performed at the bit speed of the serial link and thus require higher performance circuits.

TABLE I
DEVICE PARAMETERS AFTER COMPLETION OF WIRING AND AFTER
ANNEALING AT 375°C FOR 1 AND 2 h (The values are averages of the sites
on a typical 2-in wafer.)

Parameter	Initial	1 Hr	2 Hrs
1 μm I-FET threshold voltage (V)	0.181	0.150	0.150
1 μm D-FET threshold voltage (V)	-0.516	-0.544	-0.546
1 μm I-FET K factor ($\text{mA } \mu\text{m}^{-2}$)	0.170	0.158	0.157
1 μm D-FET K factor ($\text{mA } \mu\text{m}^{-2}$)	0.133	0.126	0.127
I-FET Schottky diode clamping voltage (V)	0.718	0.708	0.710
Ohmic contact resistance ($\Omega\text{-mm}$)	0.134	0.296	0.353
Source/drain sheet resistance ($\Omega/\square$)	348	349	349
Gate metal sheet resistance ($\Omega/\square$)	6.16	6.16	6.15
Ohmic metal sheet resistance ($\Omega/\square$)	1.15	1.22	1.20
Wiring level 1 sheet resistance ($\Omega/\square$)	0.06	0.09	0.10

lift-off profiles (used in the wiring levels). Although the optoelectronic circuits reported here only used 1.0- μm gates, isolated 0.5- μm gates have also been demonstrated with this process, indicating an even higher speed potential for these circuits.

Circuits of this level of integration require two full levels of global wiring in addition to the Ni-Au-Ge contact metal. The first and second level wiring films consist of 500 and 700 nm of Au, respectively, with 10 nm of Ni at the bottom to improve film adhesion. Three insulating films deposited by PECVD are used. Generally the first level of insulation is 500 nm of Si_3N_4 since its high tensile stress reduces the dependence of V_T on the gate length and increases the FET K factor. The second level of insulation is 700 nm of SiO_2 used because of its lower dielectric constant and stress. Vias in the insulating films are formed by reactive-ion etching using a CF_4/O_2 process that gives an edge slope of about 45 degrees to allow good coverage

by the successive metal film. An additional layer of PECVD SiO_2 is deposited on top of the second layer of global metal for scratch protection and vias are etched at the pads.

The refractory-gate metallurgy, as well as the Ni-Au-Ge process with *in-situ* sputter clean used here [9], were chosen for their relatively good thermal stability. In order to access the stability of the metallurgy, wafers were tested after completion of the wiring levels, and then again after 1 and after 2 h of annealing at 375°C. The results, which are summarized in Table I, suggest that all parameters remain within acceptable limits after annealing. The change in V_T of about 30 mV appears related to relaxation of the stress of the dielectric overlayer. FET's oriented at right angles to those reported here show a similar change in the opposite direction. No significant change in V_T is observed during the second hour of annealing. The change in ohmic contact resistance for the circuit data shown in Table I was the closest to being unacceptable, and off-line experiments have indicated a way to lower these variations.

III. FULLY INTEGRATED, SELF-CLOCKED OPTICAL RECEIVER OEIC

We have used the above technology to fabricate a 1-Gbit/s optical receiver containing the photodetector, amplifier, decision and bias control circuits, and clock recovery circuits necessary for an optical data link interface. A photo of this chip is shown in Fig. 2. These circuits have been described separately elsewhere [10], [11], so their performance will only be summarized, pointing out where the above chip devices and processes aided functional performance. This paper is the first report of the combined operation of these functions on a single chip. These functions are the most noise and jitter sensitive functions in the link, as well as being a mix of analog and digital circuits, and therefore are a good testbed of the requirements for an OEIC. The total device count on the chip is ~ 2500 , making it the most complex OEIC chip yet reported. It dissipates ~ 300 mW of heat.

A. Optical Receiver

The receiver schematic is shown in Fig. 3, and consists of an interdigitated, metal-semiconductor-metal,

Fig. 2. Photo of the receiver/clock recovery portion of the chip. The space occupied by this much function is $\sim 3 \text{ mm}^2$.

Fig. 3. Schematic of the receiver/clock functions: These are the functional blocks in the integrated receiver/clock. References [10], and [11] contain a more complete description of these circuits.

Schottky-barrier (I-MSM) photodiode, a transimpedance preamplifier, a four-stage, differential cascode-type amplifier, a Schmitt trigger decision circuit, and an automatic bias control circuit for the preamplifier. The I-MSM detector utilizes the WSi gate metal because of its optimal Schottky-barrier height, and to assure a temperature and time stable Schottky barrier for its contact fingers. The enhancement implant of the MESFET process was used under the detector to create a region that prevents surface trapping of photogenerated carriers, and thus prevents tails in the PD pulse response. The resulting dark current is 5 nA, and the measured (by optical picosecond probing technique) optical bandwidth is 14 GHz. The active area of the detector was about $5.5 \times 10^{-5} \text{ cm}^2$ making it useful with multimode fibers. Low input capacitance to the amplifier is important for high-sensitivity receivers. The

I-MSM PD design yields a low PD capacitance of 150 fF, while the ability to integrate the detector close to the preamp yield a parasitic capacitance of $< 20 \text{ fF}$. The sensitivity at 1 Gbit/s has been measured to be -22 dBm for an NRZ code and $BER < 10^{-9}$. The modeled receiver bandwidth is $> 1.5 \text{ GHz}$ with a -24-dBm sensitivity, so that we expect a packaged chip to operate at over 2-Gbit/s speed.

The receiver circuit was designed to be entirely differential to improve its immunity to power supply noise and reduce its dependence on threshold voltage. This differential design and the use of a tight detector/amplifier coupling, possible only in a fully integrated design, resulted in little noise being coupled into the receiver input from other circuits on the same chip. Differential designs do require more transistors to implement, but a technology

Fig. 4. Chip performance: Oscilloscope plot (a) shows a nominal input light level (-16 dBm) to the receiver (measured by a commercial high-speed photodiode); plot (b) is the data output; plot (c) is the recovered clock output. Horizontal scale is 2 ns/div.

with LSI IC capability means that transistors are a cheap commodity. This abundance of logic circuit capability becomes very important when designing real systems, which often have link monitoring and service functions to perform along with data transmission operations.

B. Clock Recovery

Fig. 3 also shows the schematic of the phaselock loop (PLL) clock recovery circuit. To make the chip less susceptible to noise, and take advantage of the digital characteristic of these MESFET transistors, digital circuits were utilized in the voltage-controlled ring oscillator (VCO) and the loop filter (a digital filter using up-down counters). Once again, differential circuits were employed in the PLL to prevent signal distortion and improve speed. The rms jitter measured is less than 25 ps at 1.25 Gbit/s, and the locking range was ± 10 percent of the bit rate.

C. Fully Integrated Performance

Fig. 4 shows typical operation of both clock and receiver on the same chip. Oscilloscope plot (a) is the 1.25 Gbit/s, $2^7 - 1$ pseudorandom sequence input from a laser illuminating the receiver's photodiode (optical power nominally -16 dBm). Oscilloscope plot (b) illustrates the recovered data output from the receiver, and (c) is the

Fig. 5. Noise immunity of receiver: Oscilloscope photo of receiver with no light input and free running clock on the chip operating at nominal bit rate. Top trace is clock signal output; bottom trace is receiver output. Horizontal scale is 1 ns/div. Vertical scale is arbitrary.

recovered clock. A $1/10$ -speed "byte clock" output is also available.

An important question associated with the integration of an optical receiver with large amounts of digital logic is the on-chip feedback from the digital circuits to the front end of the amplifier. Fig. 5 indicates the potential of excellent noise immunity arising from complete functional integration on a single chip. Shown in the oscilloscope trace is the receiver's amplifier when no optical input is illuminating the photodiode, taken while the clock on the chip is free-running at the bit speed, and driving a bit speed signal off the chip. On-chip noise would show up as a pattern effect at the output of the amplifier, and such patterns were not measurable.

IV. CONCLUSION

In conclusion, we have described an OEIC process and devices which are attractive to use in link adapters for optical multiprocessor networks. We have demonstrated a fully integrated optical receiver, with clock recovery, which is state of the art for integration complexity in high-speed OEIC chips. As the electronic technology is built on a digital LSI IC base, other digital circuits can be readily integrated onto this chip, and results will be reported elsewhere.

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